Emerging NASA Missions
and
Challenges in Spacecraft Control

5th International ESA Conference on Guidance, Navigation and Control Systems
October 22 – 25, 2002

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Three Eras Of Deep Space Exploration

Era 1: (1960-1975) "Just get there"

- Enabling technologies for interplanetary space travel
- Inner planets and Earth's moon

Era 2: (1975-1995) "What is out there?"

- Survey planets and their moons with large spacecraft
- Outer planets and moons

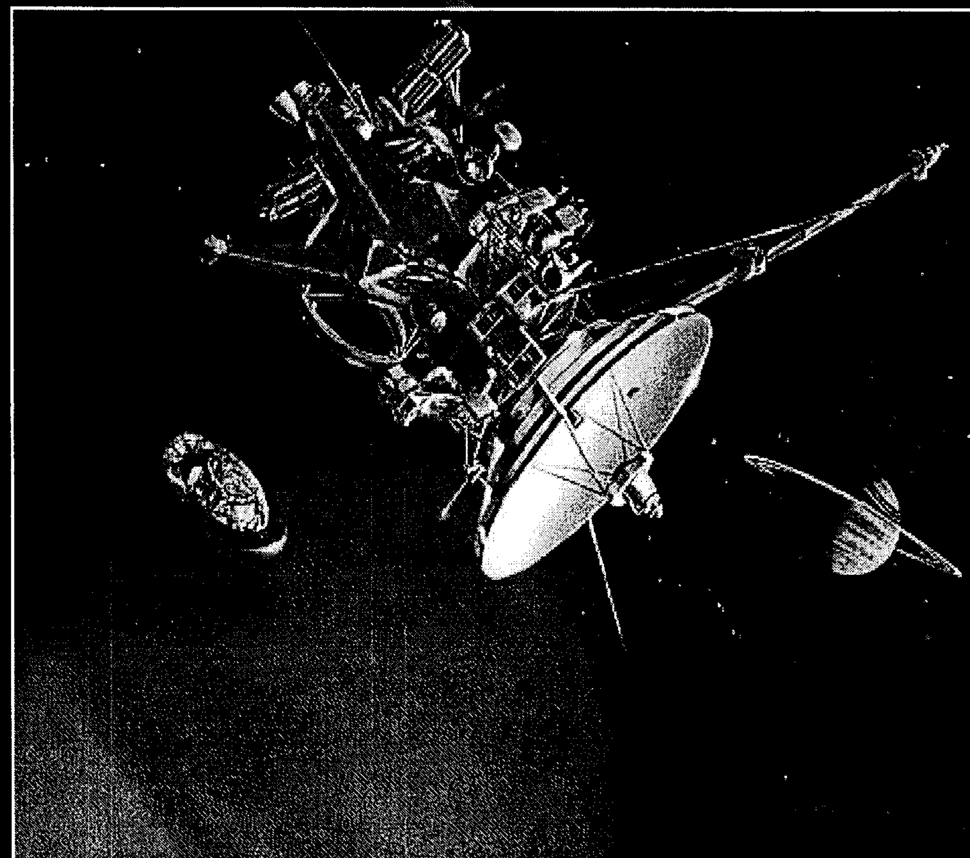
Era 3: (1995-?) "Smaller, frequent and focused missions"

- High levels of autonomy (less contact with Earth)
- New mission types

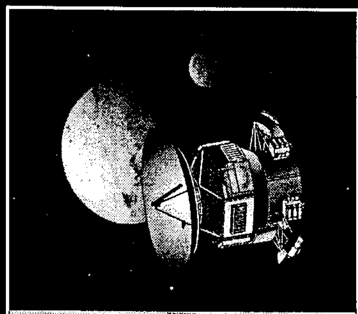
Past Approach

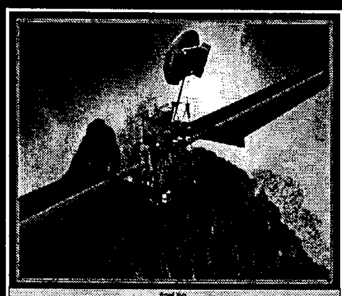
LARGE SPACECRAFT

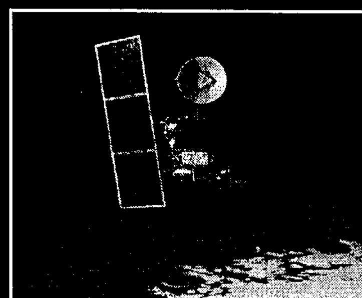
- Billion Dollar Missions
- One Big Mission at a Time
- Significant Ground Involvement
- Long Mission Life
- Low Risk Tolerance
- Proven Technologies Only

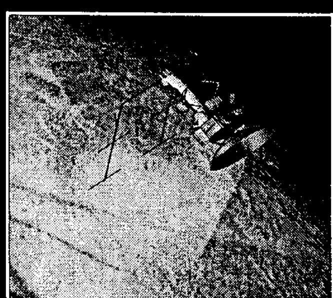


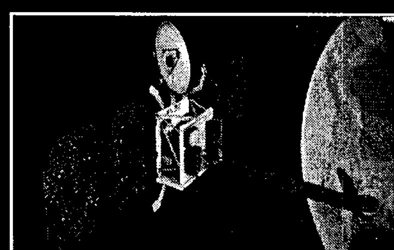
The New Paradigm











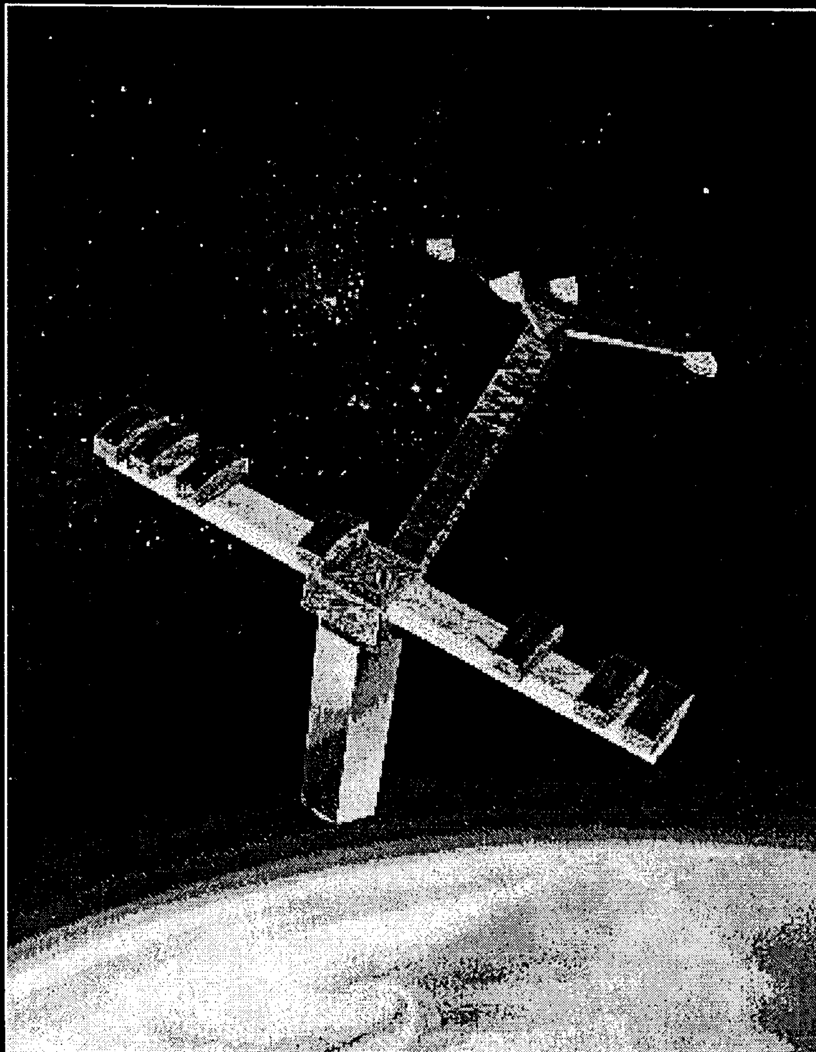
SMALL SPACECRAFT

- *Faster, Better, Cheaper*
- *More Missions, Shorter Development Cycles*
- *High Levels of Autonomy*
- *New Missions Types*
- *Rich in Technology, Higher Science Return*
- *Willingness to Take Risk*
- *Not Optimal but Good Enough*

Deep Space Control Challenges

- **Precision Landing on a Small Bodies**
  - Irregular Spinning Body, Uncertain Disturbance Environment
- **Formation Flying**
  - High Precision Coordination and Control
  - Formation Maneuvers and Station Keeping
- **Robotic Exploration of Planetary Surfaces**
  - Intelligent Capable Rovers
- **Autonomous Rendezvous and Docking**
- **Inflatable Structures and Balloons**
  - Shape Control, Vibration Suppression
- **Interferometry**
  - Large Space Structures, Multi-Body
  - Integrated Optical, Structural, Thermal control

Space Interferometry



- Space Interferometry Mission (SIM)
  - Telescopes separated by 10 m
- Optics controlled to nanometer accuracy
- Relative knowledge and metrology to a trillionth of a meter
- Large flexible structures control
- Embedded micro G&C sensors & actuators
- Integrated modeling
  - Structures, thermal, optics, controls, and dynamic disturbances

Space Interferometry

Control Testbed

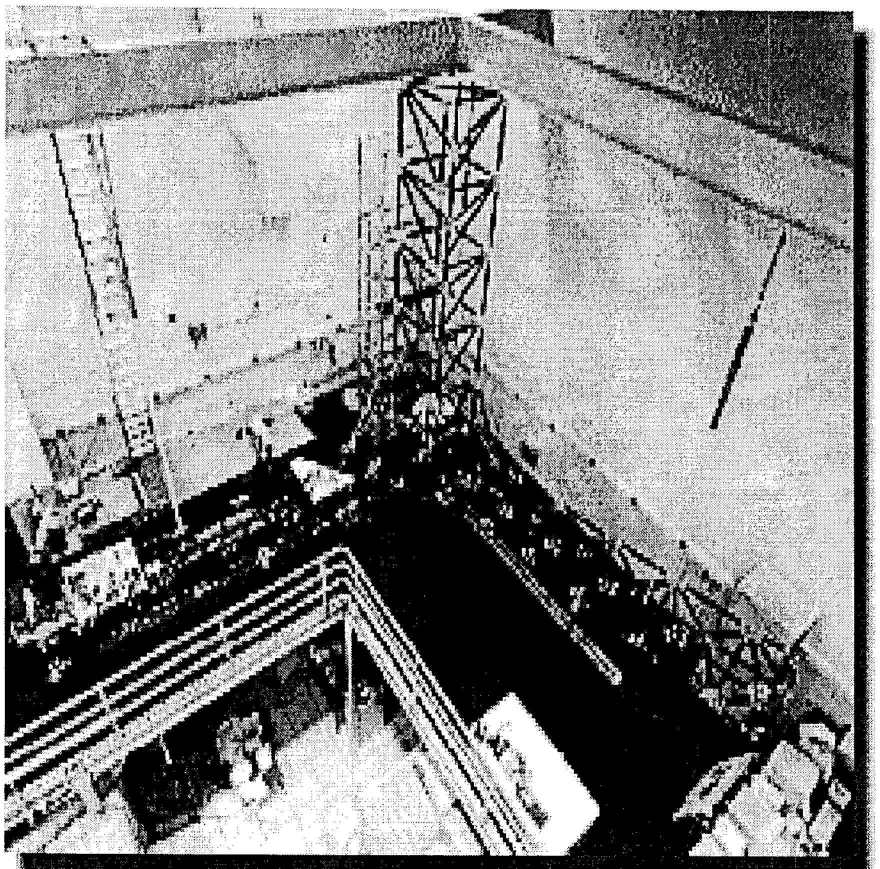
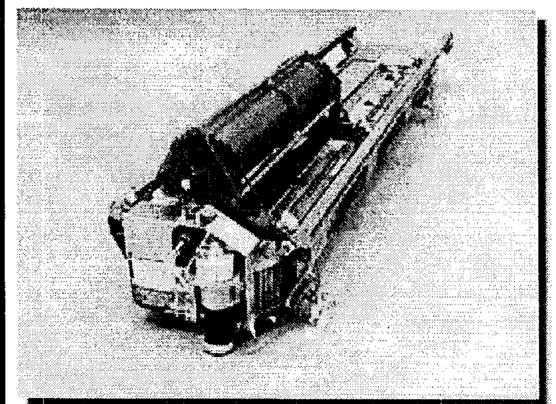


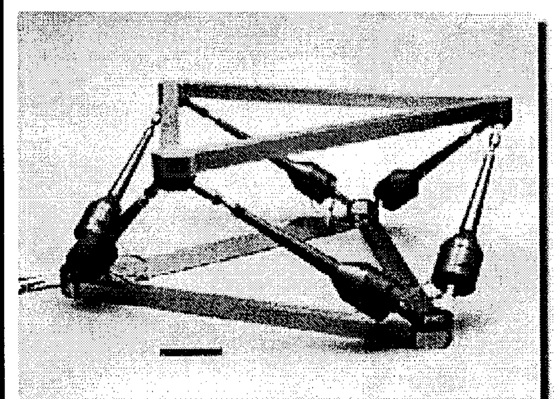
Figure 1. Bird's eye view of the MPI tesbed.

Optical path length control



The Optical Delay Line is designed to equalize the optical path length of the two arms of the Interferometer tobetter than 5 nanometers rms.

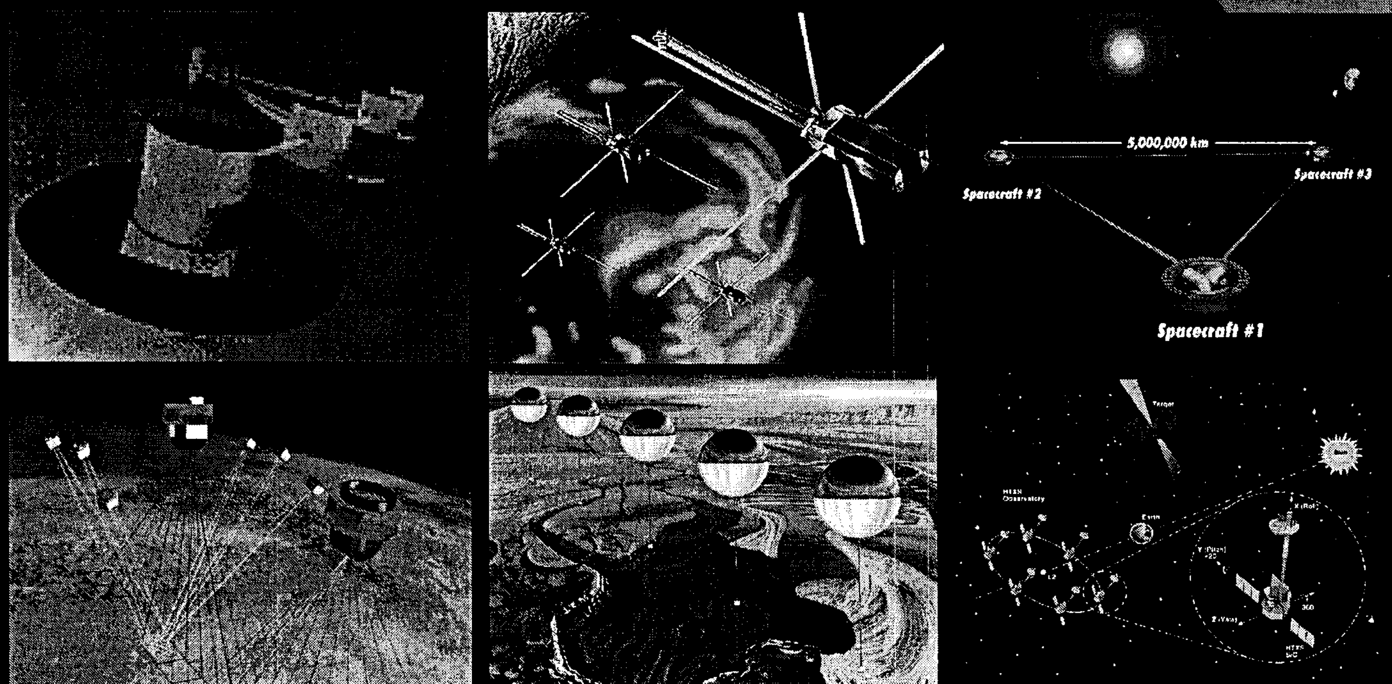
Active Vibration Suppression



Six axis active vibration isolator

Formation Flying Spacecraft

A Set of Spatially Distributed Spacecraft Flying in Formation with the Capability of Interacting and Collaborating with One-another, and Work as a Single Collective Unit, Exhibiting a System-wide Capability to Accomplish Shared Objectives



Future Formation Flying Mission Concepts

ORIGINS
Galaxies, stars, planets... and life.

Structure & Evolution of the Universe

THE SUN EARTH CONNECTION

STP
SOLAR TERRESTRIAL PROBES
NASA GODDARD SPACE FLIGHT CENTER

LIVING WITH A STAR
LWS
NASA Goddard Space Flight Center

Destination: Earth

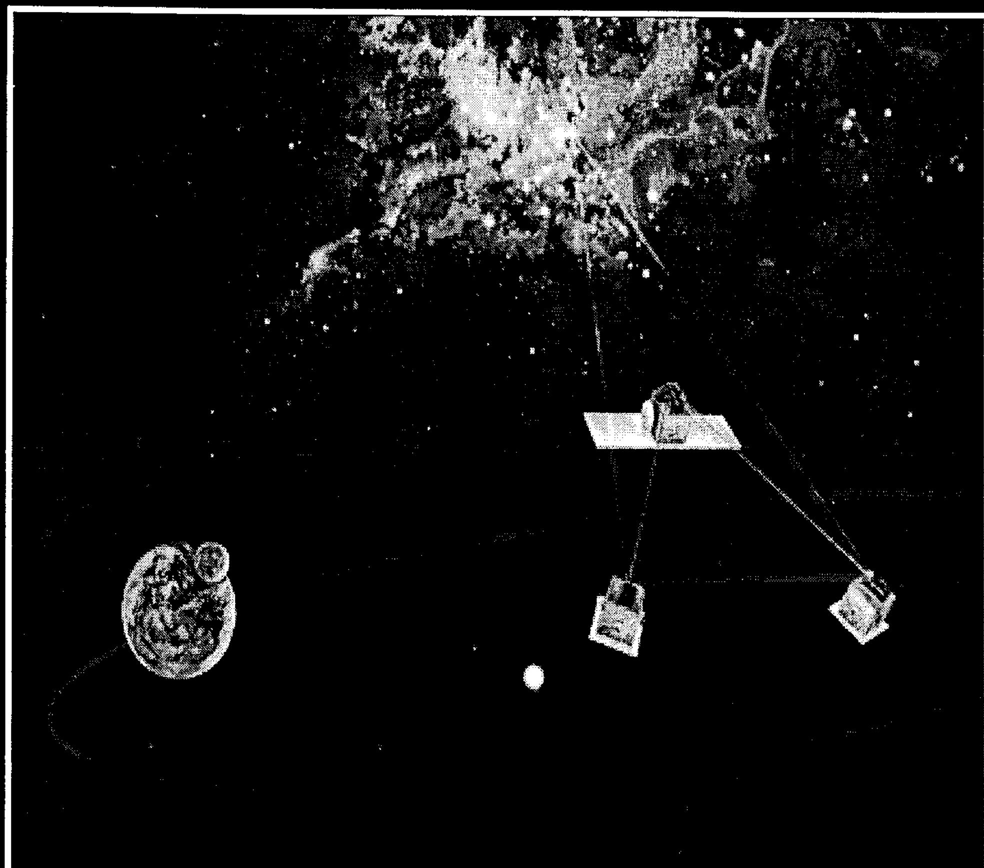
Partial List of Science Investigations Enabled by Distributed Spacecraft Systems:

- Planet finding and imaging
- Resolving the cosmic structure
- 3-D mapping for planetary explorers
- Time-varying gravity field measurements
- Gravity wave detection
- In situ magnetosphere and radiation
- Electrodynamics environment of near-Earth space
- Earth radioactive forcing
- Soil moisture and ocean salinity
- Atmospheric chemistry
- Global precipitation
- Coordinated observing for land imaging
- Vegetation recovery
- Space weather

Technology Challenges

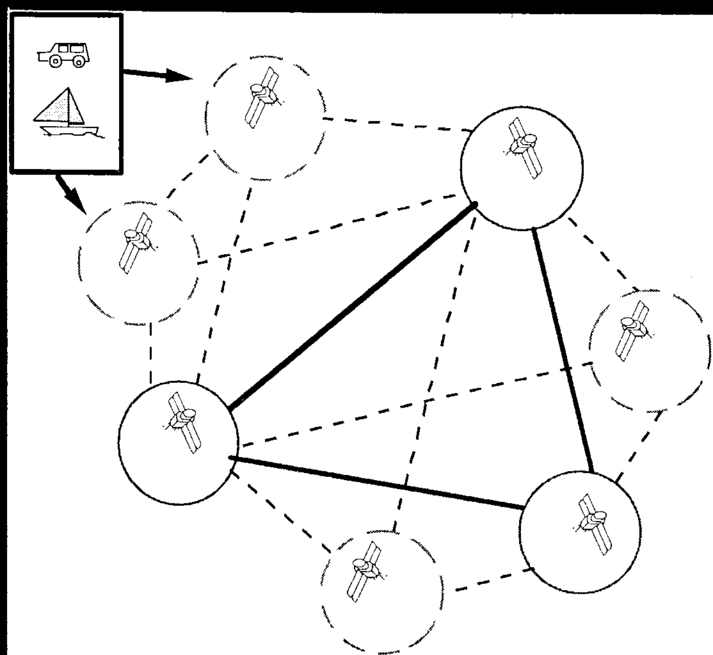
- **Formation control**
  - Hi precision sensors
  - Synchronous fleet reconfiguration/reorientation
  - Decentralized distributed control and estimation
  - Relative/absolute position and attitude control for precision interferometry
- **Extremely high precision/low noise thrusters, wheels, etc.**
- **Communication, cross-links, downlinks**
- **High speed distributed computing, data management & autonomy**
  - Collaborative behavior
  - Autonomous fault detection/recovery
  - Coordinated instruments and science planning/processing
  - Efficient numerical integrators which handle large scale variations in states (relative position and attitude)
- **High fidelity modeling and distributed real-time simulation**
- **HW Testbeds**
  - Ground testing of 6dof

Formation Flying Control



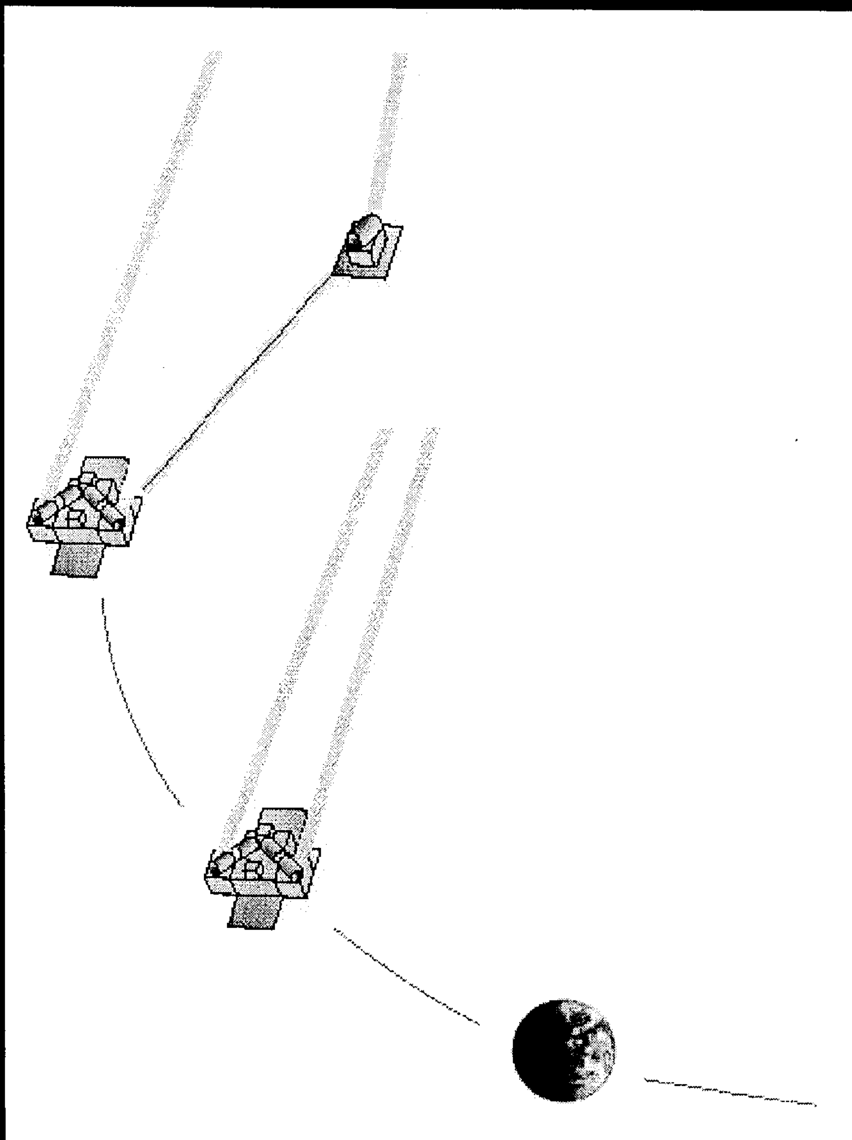
- Precision Constellation of Multiple Spacecraft Form a Single Virtual Science Instrument
- Increased Performance, Accuracy and Reliability
  - Interferometric Imaging Without Large Truss
  - Distributed Computing via Interspacecraft Communication
  - No Single Point Failures
  - Autonomous Formation Keeping, Alignment and Reconfiguration

Autonomous Formation Flying (AFF) Sensor



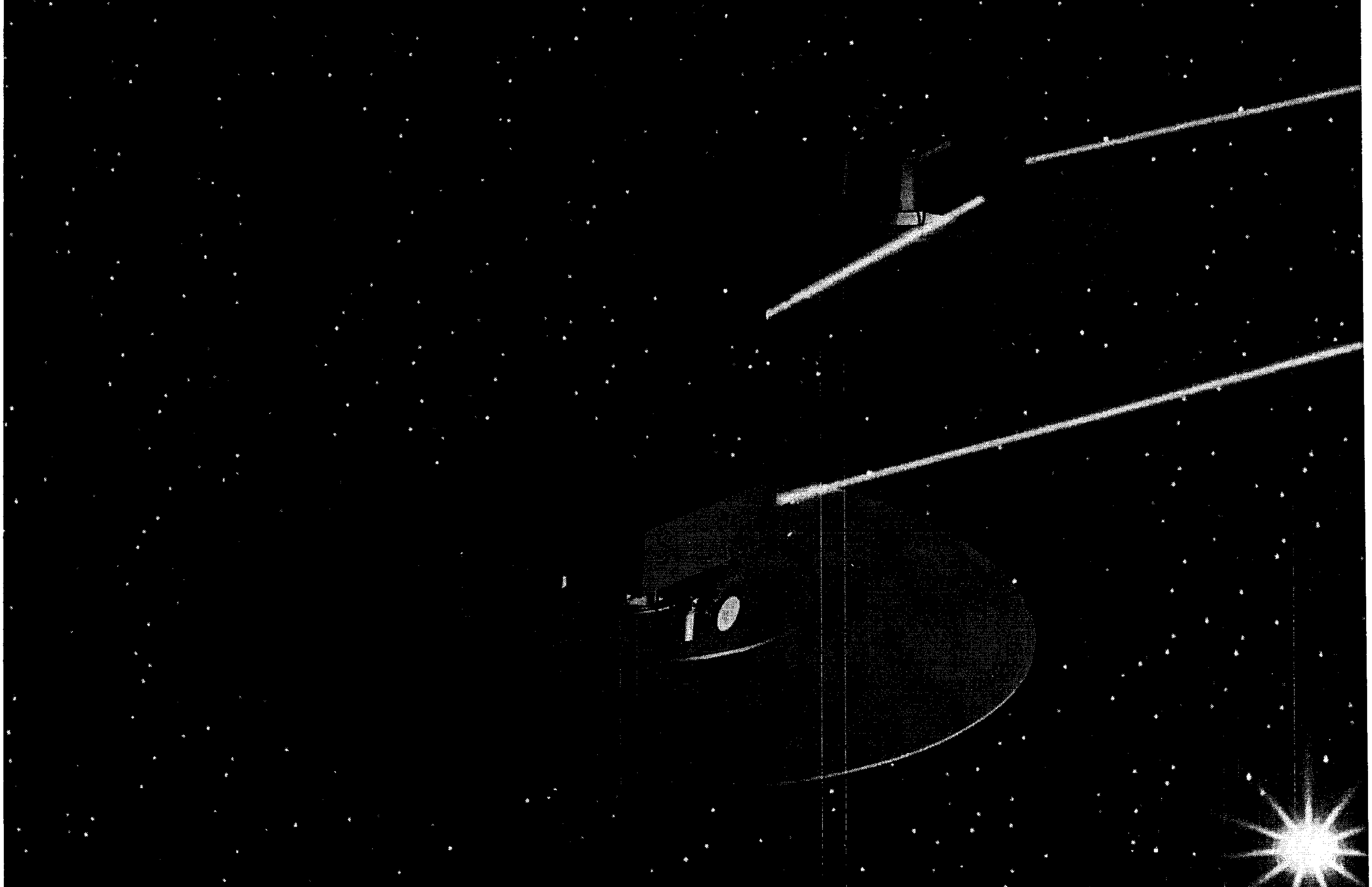
- Autonomous Formation Flying GN&C Sensor (AFF)
  - Similar to a GPS ADS but with 6 receive antennas and 2 receive antennas
    - 4pi steradian coverage (FOV)
  - Provide relative measurements: attitude, attitude rates, range, range rate and time
  - Ideal for multiple spacecraft in Earth orbit and deep space
    - Formations and constellations
    - Rendezvous and docking
    - Self contain system, does not require NAVSTAR GPS satellites' signals
      - But can accommodate if necessary
  - High performance relative measurements
    - ±1 cm ranging, ±1 mm/sec velocity, ±1 arcminute attitude
    - 1m to 1300km operational range as designed

Starlight

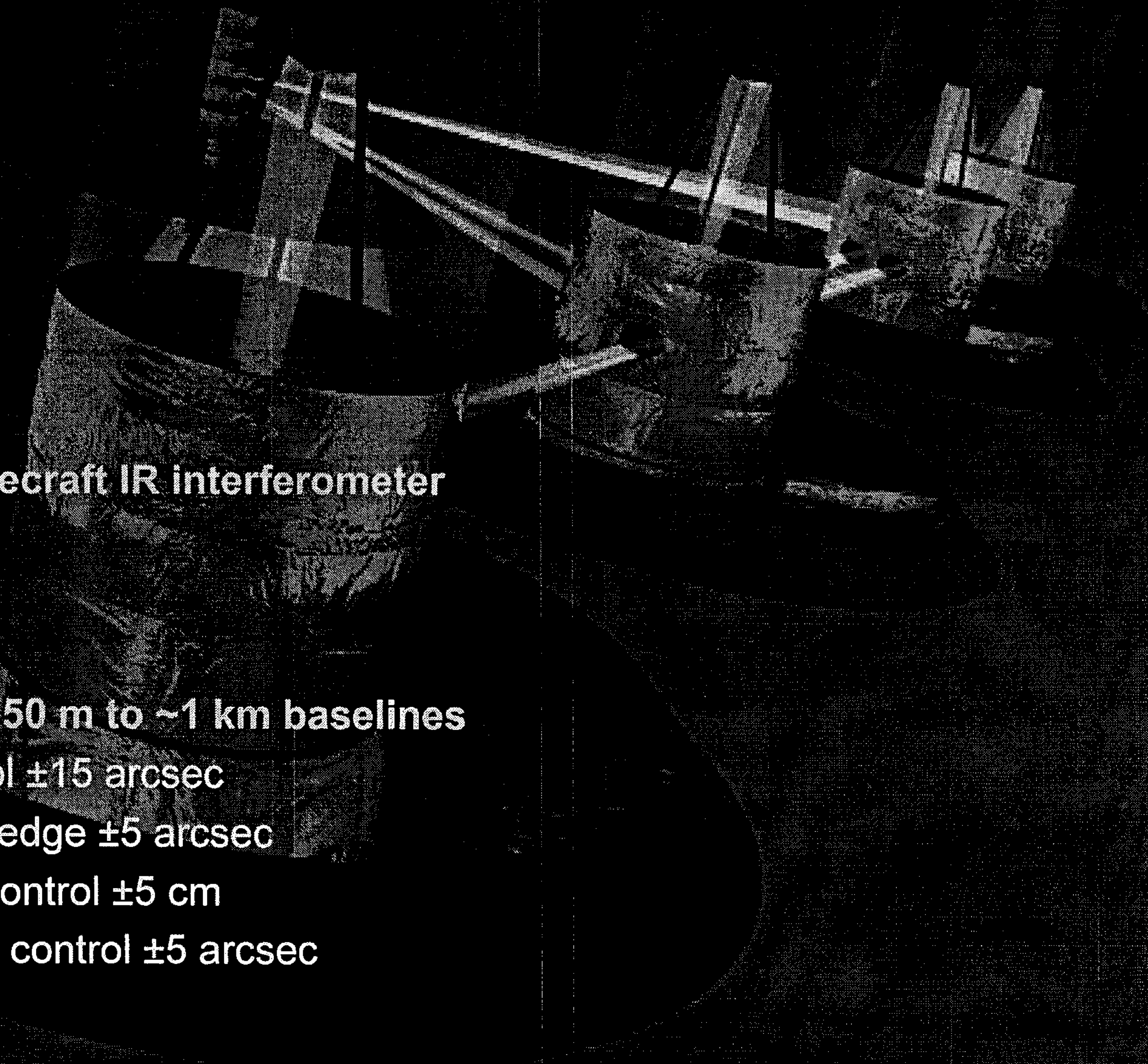


- **Two (2) S/C mission**
- **Technology demonstration for TPF**
  - Formation flying
  - Separated S/C optical interferometry
- **March 2004 launch**
  - Delta II 7325
- **Heliocentric orbit**
- **6 month mission**
- **GN&C Requirements**
  - 50 to 1010 m baselines
  - S/C attitude control ±1 arcmin
  - S/C attitude knowledge ±10 arcsec
  - S/C translational velocity control ±0.1 mm/sec
  - Formation range control ±3 cm
  - Formation bearing control
    - Acquisition ±0.7 arcmin
    - Observation ±6.7 arcsec

Starlight



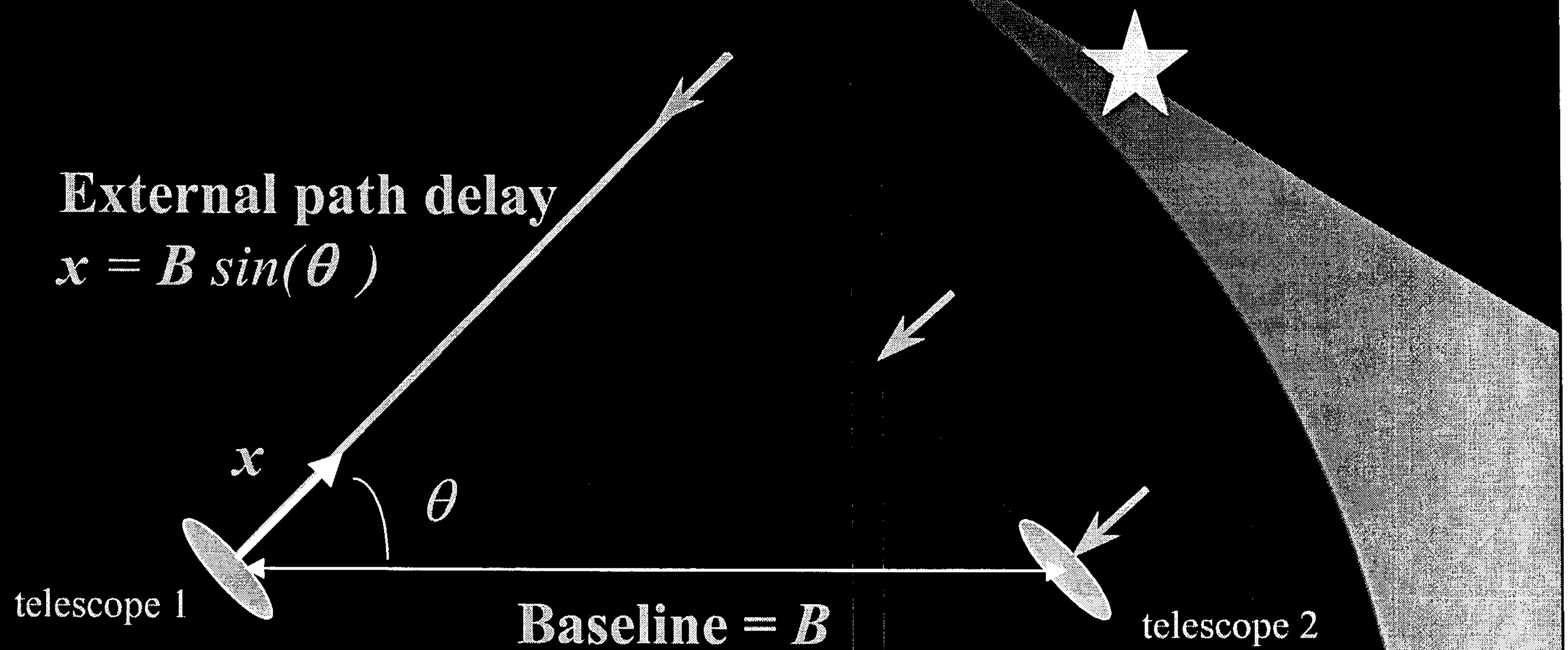
Terrestrial Planet Finder (TPF)



- **5 S/C separated spacecraft IR interferometer**
- **2011 launch**
- **Heliocentric orbit**
  - Single launcher
- **GN&C Requirements 50 m to ~1 km baselines**
  - S/C attitude control ±15 arcsec
  - S/C attitude knowledge ±5 arcsec
  - Formation range control ±5 cm
  - Formation bearing control ±5 arcsec

Astrometric Measurement

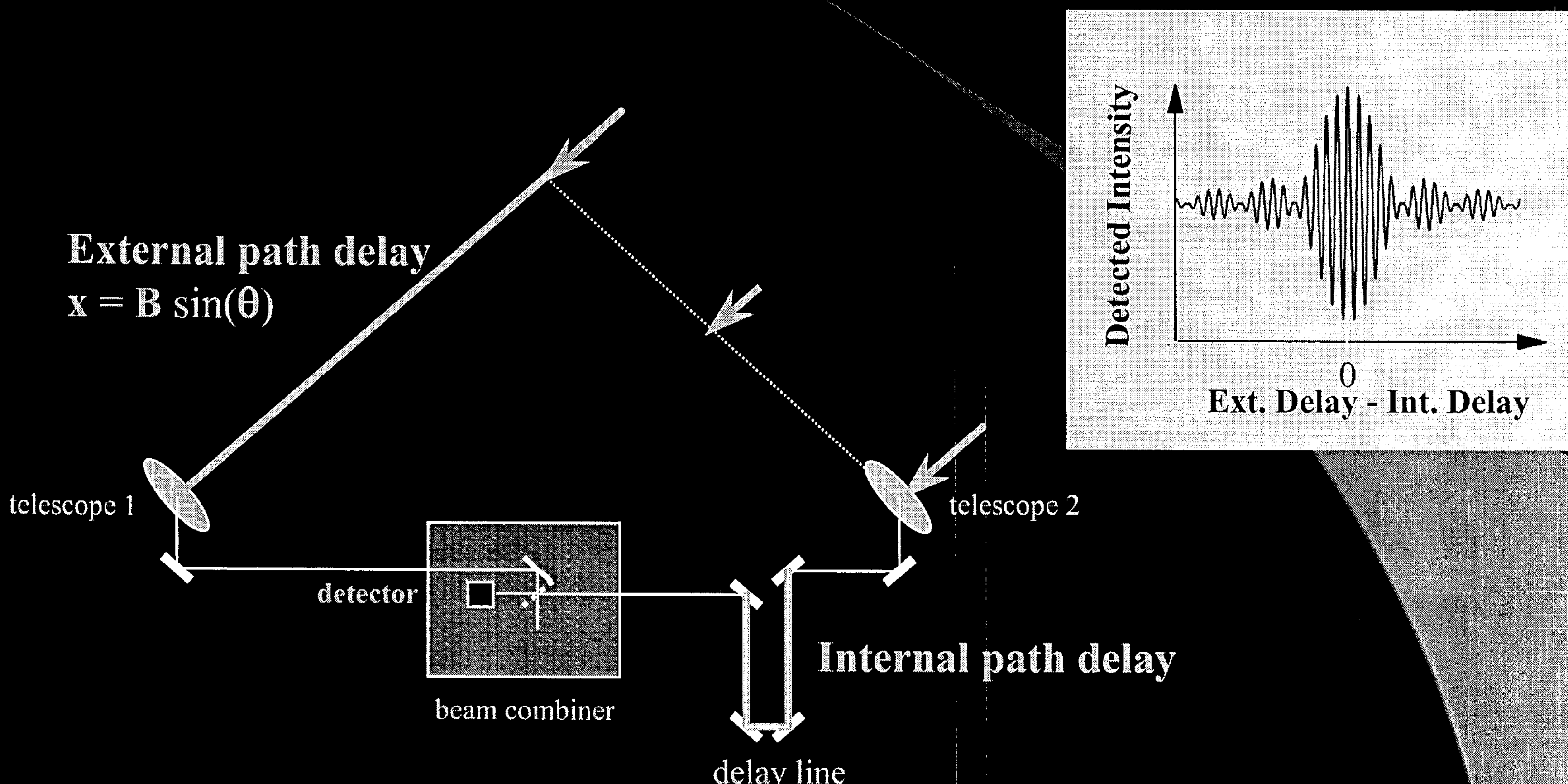
(want to know θ with high level of accuracy)



If you know B & can determine x , then we can sole for θ

Astrometric Measurement

(want to know θ with high level of accuracy)

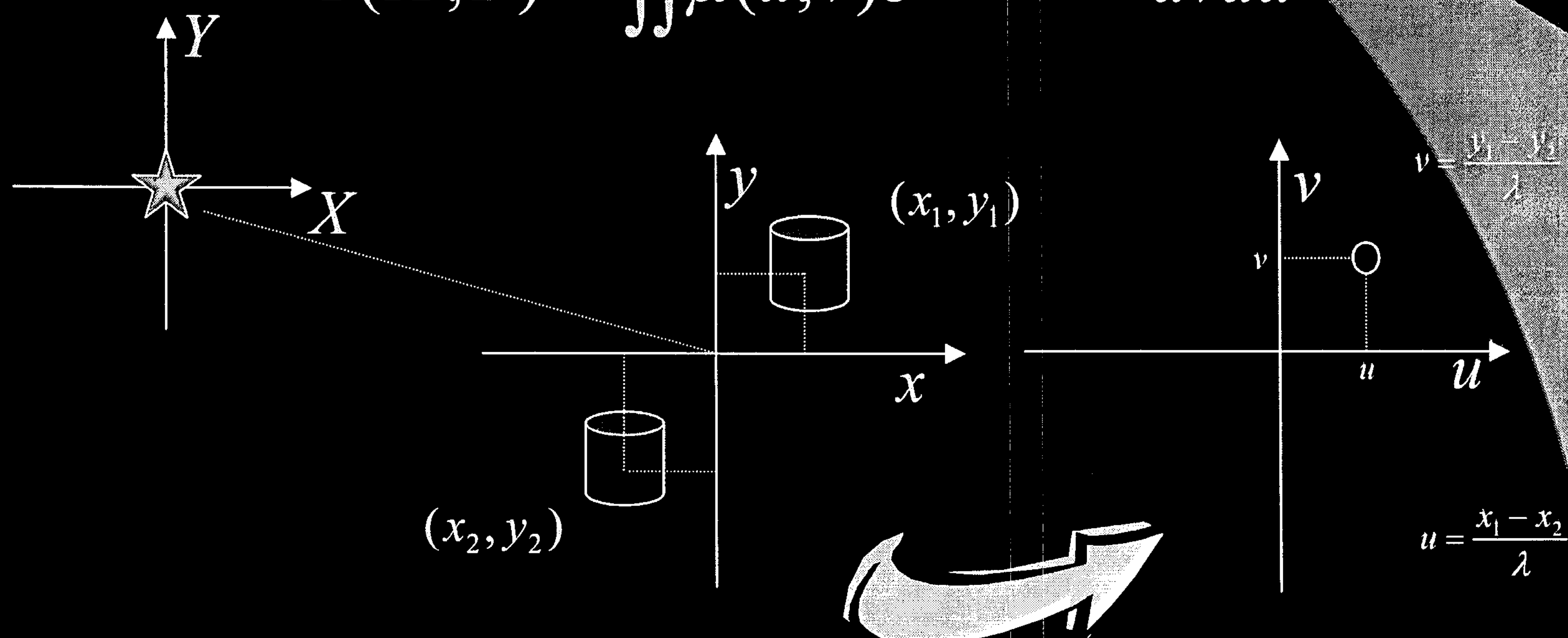


- ***The peak of the interference pattern occurs when the internal path delay equals the external path delay.***
- ***Internal metrology measures internal path delay***

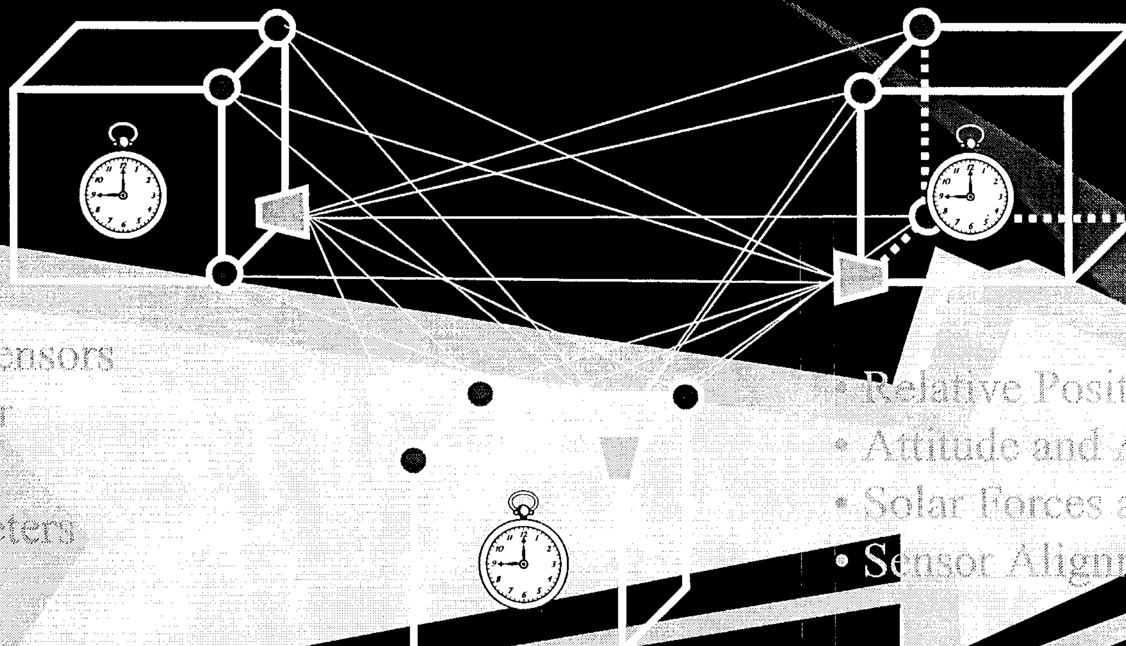
Formation Flying Control

The essential relationship used for imaging is expressed by the Cittert-Zernike formula.

$$I(X,Y) = \iint \mu(u,v) e^{i2\pi(uX+uY)} dv du$$



Formation Flying Estimation Challenges



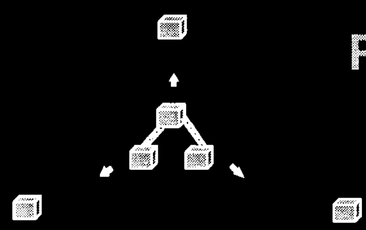
- AFF GPS sensors
- Star Tracker
- Gyro
- Accelerometers
- Metrology

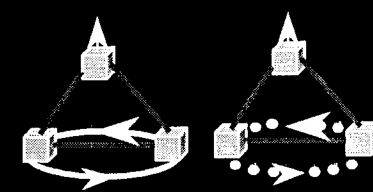
- Relative Position and Velocity
- Attitude and Angular Rate
- Solar Forces and Torques
- Sensor Alignments and Biases

- Order n^2 state estimation problem
- Centralized/decentralized
- Asynchronized data type
- Integrated position/attitude estimation
- Relative state (position or attitude) estimates are highly coupled

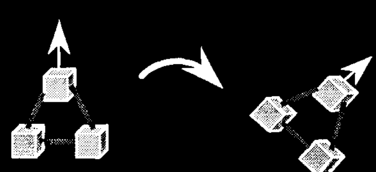
F. Y. Hadaegh - JPL

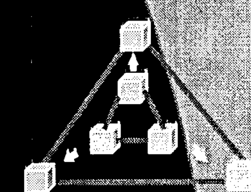
Formation Flying Control


Formation Initialization


Formation Observation Slew

- **Products:**
  - System of methods, architectures, algorithms and software for autonomous precision control (mm-cm, arcsec-arcmin) of formation flying spacecraft.
    This include:
    - formation acquisition,initialization & maintenance, station keeping
    - formation maneuver planning and execution
    - fault detection and recovery
- Underlying Technologies:
  - Autonomous guidance and control algorithms, software, and testbeds
    - Scalable FF control architectures
    - Autonomous guidance and control laws
    - Formation estimation algorithms
    - Testbed Demonstration of precision translation and synchronized rotations
    - Precision formation controls optimized for time and/or fuel
    - Data fusion of high number of formation sensors across many spacecraft
    - Algorithms for optimal u-v plane mapping of science target
    - Optimal Path planning
    - Collision avoidance


Formation Retargeting Slew


Formation Resizing

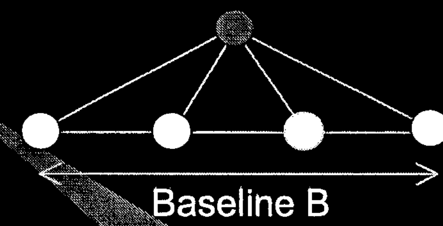
What You Will See in the Demos

- **TPF Type Formation Guidance Path Planning**
  - Autonomous Control of Formation Spacecraft
  - Autonomous Reconfiguration
  - Collision Avoidance
  - Optimal Path Planning
  - Precision Synchronized Motion

TPF FF Guidance & Control Demo

Spacecraft Description and Sequence of Events

- 600-700 kg class S/C
  - Sun shade diameter: 15 m for collectors, 12 m for combiner
  - Only collectors equipped with a telescope
- Processing @ 1 hz
- Hardware
  - Thrusters (12 on each S/C, combination of 2N, 5N thrusters – highly coupled attitude, translation)
  - AFF, 6 axis IRU, Tracker on each S/C
  - AFF FOV (80° half-cone) tailored to meet TPF configuration
- Sequence of events:



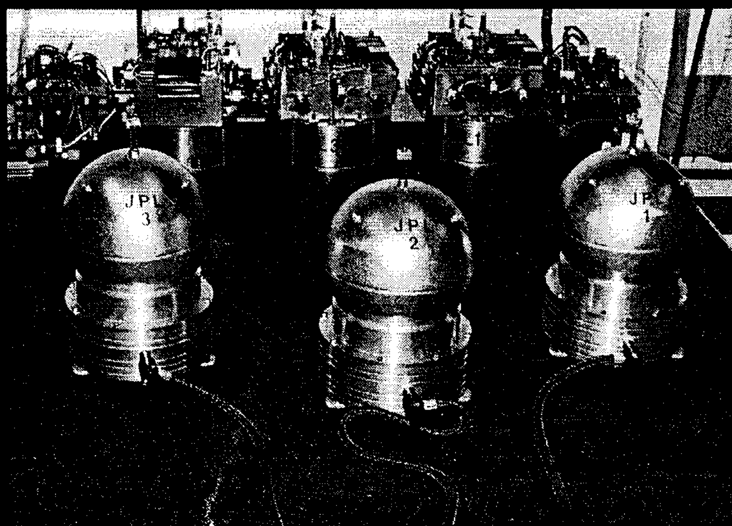
Initialization

[0 s]	Stacked cluster, combiner in the middle, heliocentric, 1 AU behind earth
[10 s]	Staggered, passive, timer-based, deployment (push-off springs)
[200 s]	Null separation delta V and hold attitude (IRUs only – **NO AFF, Star Tracker inputs yet**)
[300 s]	Go to the TPF configuration
	- 80 m baseline, inertial target = [0.267, 0.535, 0.8018], collision avoidance radius = 10 m
	- Duration 300 sec
	- **NO AFF, Star Tracker inputs yet**
[650 s]	**Enable AFF, tracker data – update formation, attitude estimates**
[750 s]	Deploy cover, secondary optics

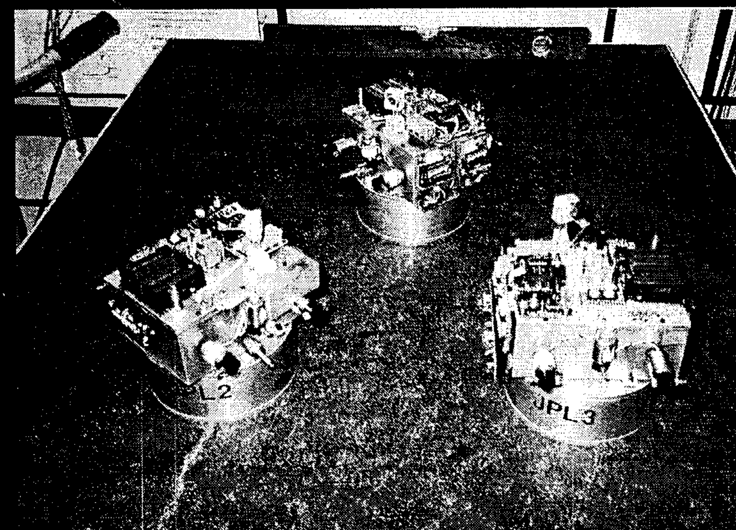
[950 s]	Expand baseline to 120 m - duration = 150 sec, same inertial target, baseline orientation
[1250 s]	Contract baseline to 80 m - duration = 150 sec, same inertial target, baseline orientation
[1600 s]	Reconfigure - reassemble 150° away, duration = 300 sec, same inertial target (No sych. rot.)
[2100 s]	Synchronized rotation - 150° arc, broken into 10 linear segments, total duration = 1500 s (IF)
	- 0.1°/sec formation rotation rate

Formation Maneuvers

Formation Flying Control Testbeds



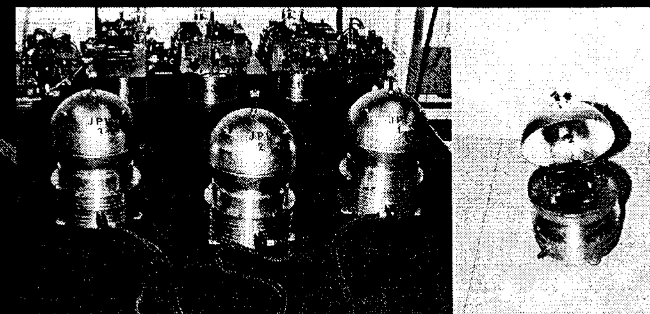
Precision *Attitude*
Determination/Control Testbed

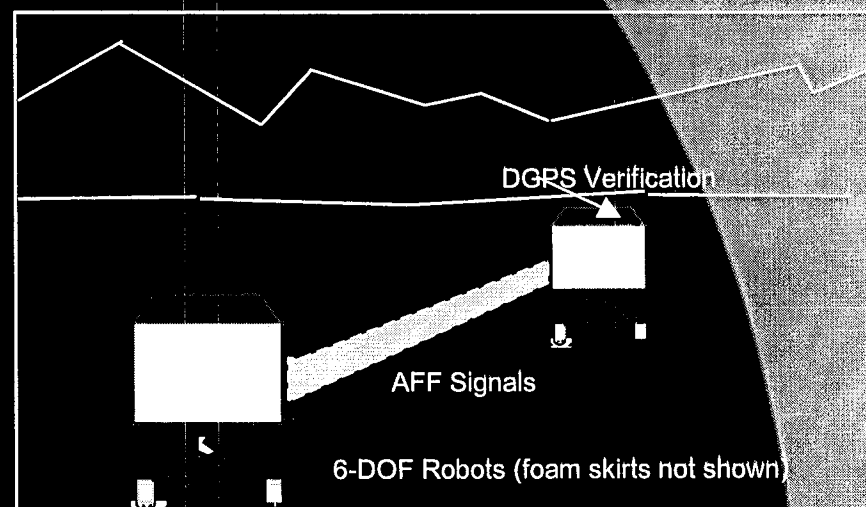


Precision *Position*
Determination/Control Testbed

UCLA/JPL Formation Flying Testbeds to Demonstrate Precision FF Control & Reconfiguration

Formation Flying Ground Testing





- **End-to-end formation flying performance demonstration**
  - Closed-loop demo between H/W & S/W
  - Large scale demo
- **Testbed facility & description**
  - 6-DOF wheeled robots with accurate S/C models

Summary

- Many New and Exciting Future Deep Space Missions
- Intelligent Space Vehicles with Higher Levels of System Autonomy
- New Control System Development Approaches and System Architectures